

GAMMA-RAY IMAGING OBSERVATIONS OF POINT SOURCE EMISSION FROM THE GALACTIC CENTER REGION

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Abstract

The first coded-aperture images of the galactic center region at energies above 30 keV reveal two strong γ -ray sources. One source is tentatively identified as the X-ray source 1E1740.7-2942. If this source is at the distance of the galactic center, it is one of the most luminous objects in the galaxy at energies from 35 to 200 keV. The second source is consistent in location with the X-ray source GX354-0. No significant flux was detected from the direction of the galactic nucleus (Sgr A*).

Introduction Recent results from *Spacelab 2* (Skinner *et al.* 1987) and *Spartan 1* (Kawai *et al.* 1988) between 1 and 30 keV, together with earlier results from the *Einstein* observatory between 0.9 and 4 keV, (Watson *et al.* 1981, Hertz and Grindlay, 1984) have identified several point sources within approximately one degree of the galactic nucleus, including a point source at the nucleus itself. At higher energies, non-imaging observations have detected 0.511 MeV positron annihilation line radiation and hard continuum emission extending above 1 MeV from the general direction of the galactic center (e.g., Riegler *et al.* 1981, Leventhal *et al.* 1982, Riegler *et al.* 1985, Leventhal *et al.* 1989). Both line and continuum components vary in intensity on time scales as short as six months. The compact source size required by the time variability, and the unusual γ -ray spectrum, have stimulated speculation that the emission may be due to a massive black hole at the galactic nucleus. The first imaging observations of the galactic center region at γ -ray energies (30 keV - 7 MeV) are reported in this paper, which extends a preliminary analysis discussed in Cook *et al.* 1988. In particular, we have now detected an additional source in the galactic center region, and have obtained additional position information strengthening the identification of the strong galactic center source as 1E1740.7-2942.

Observations The observations were performed with the Caltech Gamma-Ray Imaging Payload (GRIP), a balloon-borne coded-aperture telescope sensitive to radiation at energies from 30 keV to 10 MeV (Althouse *et al.* 1985). The instrument employs a rotating hexagonal-celled uniformly redundant array and a NaI scintillation camera to image a 14° diameter field of view with 1.1° angular resolution. The γ -ray telescope is mounted in an elevation-azimuth pointing gondola. Magnetometer error signals are used in post-flight analysis to correct for short-term azimuthal tracking errors. Absolute aspect information is obtained from an image-intensified CCD star camera sensitive to 7th magnitude.

During a 30 hour balloon flight of the instrument in April 1988 from Alice Springs, Australia, the galactic center region was observed for two 4-hour periods during the interval 12.62 to 13.00 April 1988 UT. The data were processed in seven segments of somewhat more than one hour each. For each segment a single strong point source of γ -ray emission was detected at energies between 35 keV and 200 keV. Data was available from the star camera to determine the absolute position of the source emission in only the first four observation periods, which occurred at night. An example of one hour of data for the 35 to 200 keV energy interval is shown in Figure 1(a), obtained during the period 12.751 to 12.792 April 1988 UT. The image contains a single significant ($>6\sigma$) source peak.

An expanded view of the source region of Figure 1(a) is shown in Figure 1(b). The estimated 90% confidence error boxes for each of the observations for which star camera data were available are shown. Rectangular error boxes have been chosen with the long axis aligned with the elevation direction of the telescope and the short axis aligned with the azimuthal direction. The star camera provides aspect information primarily in the azimuthal direction, with an estimated uncertainty of 0.1° due to variations in the quality of

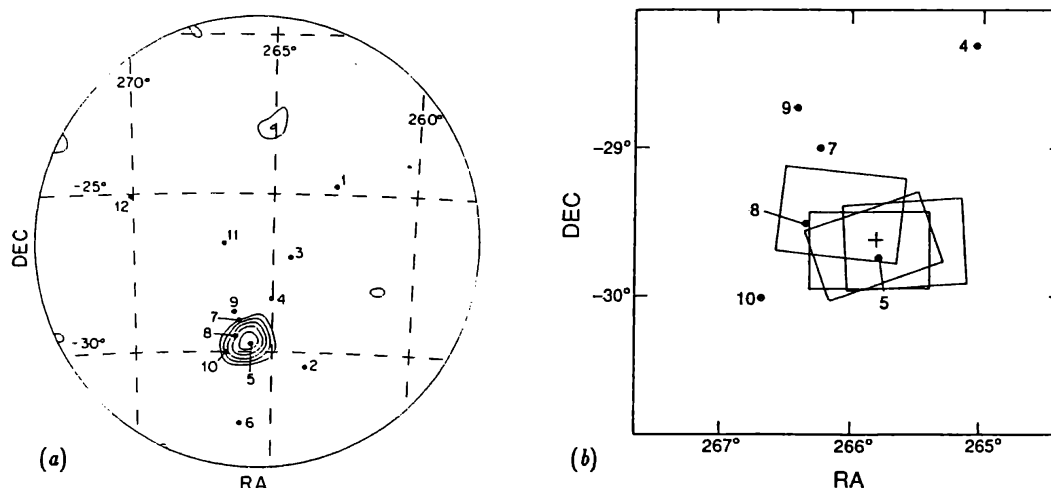


Fig. 1.—(a) Image of the galactic center region from 35 to 200 keV covering a 14° field of view. Right ascension (vertical lines) and declination (horizontal lines) are indicated for epoch 1988.3. The contours indicate the number of excess counts in a given direction, calibrated in units of the statistical significance of the excess, with contours beginning at the 2σ level and spaced by 1σ . Known hard X-ray sources (Levine *et al.* 1984, Skinner *et al.* 1987) are: (1) GX1+4, (2) SLX1732-304, (3) SLX1735-269, (4) SLX1737-282, (5) 1E1740.7-2942, (6) A1743-322, (7) Sgr A*, (8) A1742-294, (9) 1E1743.1-2843, (10) SLX1744-299, (11) GX3+1, and (12) GX5-1. (b) Expanded view showing 90% confidence error boxes for the location of the γ -ray source.

the CCD camera downlink reception. For each of the four pointings, the net uncertainty in the azimuthal direction was obtained by adding this 0.1° uncertainty in quadrature with the statistical error in the image peak location, which ranged from 0.07° to 0.10° . In the elevation direction, the aspect was determined by level sensing of the pointing platform, together with knowledge of the latitude and longitude of the gondola as determined by the NSBF OMEGA navigational system. The level of the platform was monitored by inclinometers and a non-horizontal magnetometer. We have estimated the net elevation uncertainty as 0.2° , based on the elevation pointing errors measured in seven Crab pointings and one pointing at Cyg X-1.

The model-independent most-probable source location was determined by performing a two-parameter χ^2 best fit of RA and DEC to the four position determinations. The position so-obtained, indicated by a cross in Figure 1(b), is 0.12° from source number 5, 1E1740.7-2942. The error boxes for the the peak location exclude all other hard X-ray sources shown except source number 8, A1742-294. This source is 0.46° from the best-fit peak location, and is contained in one error box. The galactic nucleus source Sgr A* (source number 7) is 0.72° away from the best-fit peak location, and is well outside any of the error boxes.

We conclude from our imaging data that the observed γ -ray source is best identified with the hard X-ray source 1E1740.7-2942, while A1742-294 is a less likely candidate. The χ^2 test mentioned above strongly favors 1E1740.7-2942. The value of $(\chi^2 - \chi^2_{\min})$ for 1E1740.7-2942 is 2.8 (for 6 degrees of freedom), while that for A1742-294 is 24.7, where χ^2_{\min} is the χ^2 value at the best fit source location position.

To obtain an energy spectrum for the source, the seven one-hour observations were added together with pointing offsets chosen to align each image peak with that of Figure 1. The resulting source spectrum is shown in Figure 2. A minimum χ^2 fit to a power law function, $dJ/dE = K(E/100\text{keV})^\alpha$, was performed for our measured spectrum in the energy range from 35 to 200 keV. The best fit power law spectrum, shown in Figure 2, has a spectral index $\alpha = -1.81 \pm 0.12$ and a flux normalization $K = 7.4 \pm 0.5 \times 10^{-5} \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$. A similar

analysis for the Crab nebula and pulsar from 35 to 173 keV gave $\alpha = -1.80 \pm 0.06$ and $K = 4.7 \pm 0.1 \times 10^{-4} \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$. Although our analysis method, in which we align image peaks, tends to slightly overestimate the γ -ray flux, the magnitude of this effect is less than four percent.

We have searched for other weaker sources by using the strong central source as a pointing reference to co-align images from the separate one-hour segments. A second source does appear in the energy range from 23 to 122 keV, as shown in Figure 3, where the primary image peak has been shifted to align with the location of 1E1740.7-2942. The secondary peak has a statistical significance of 5.5σ and its location is consistent with that of the X-ray source GX354-0 (Grindlay 1, Hertz and Grindlay, 1983). The presence of the secondary peak at the location of a known X-ray source further supports the identification of the primary peak with 1E1740.7-2942.

An image has also been generated for a 55 keV wide energy band centered on 0.511 MeV, and chosen to include 89% of the flux from a narrow line. No significant image peak was found. The preliminary 99% confidence upper limit for 0.511 MeV line flux from a point source at the position of the primary hard X-ray image peak is $8 \times 10^{-4} \text{ cm}^{-2} \text{ s}^{-1}$.

Discussion Our observations at energies above 35 keV are in good accord with the earlier imaging results from *Spacelab 2* at energies below 30 keV (Skinner *et al.* 1987). The *Spacelab 2* results show that in the 19 to 30 keV interval one source, 1E1740.7-2942 (number 5), dominates the central few degrees of the galactic center. If the source is at a distance of 8.5 kpc, its 35 to 200 keV luminosity of 1.7×10^{37} ergs/s would be comparable to the 50 to 400 keV luminosity of 2.3×10^{37} ergs/s measured for the black hole candidate Cyg X-1 in its γ_3 state (Ling *et al.* 1987).

Our measured flux falls below or near the lower envelope of previous flux measurements obtained at energies from about 50 keV to 1 MeV with non-imaging, wide aperture ($>10^\circ$ FWHM) instruments (Matteson, 1982). The higher fluxes obtained with wide aperture instruments at energies below 100 keV may be due to the inclusion of other (possibly time-variable) hard X-ray sources, such as GX354-0, located within 10° of the galactic center. Several instruments (Dennis *et al.* 1980, Matteson, 1982, Levine *et al.* 1984, Knight, *et al.* 1985) with relatively narrow apertures (1.5° to 5° FWHM) have observed a source near the galactic center with flux at 100 keV ranging from ~ 0.5 to $2.0 \times 10^{-4} \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$, comparable to that shown in Figure 2. Our observations support the suggestion by Skinner *et al.* (1987) that 1E1740.7-2942 is the most probable source for the high energy flux seen in these earlier observations.

It is interesting to consider whether the γ -ray source detected in our observations could have been the source of 0.511 MeV positron annihilation radiation and greater than 0.511 MeV continuum radiation previously observed from the general direction of the galactic center (e.g., Riegler *et al.* 1981, Leventhal *et al.* 1982, Riegler *et al.* 1985, Leventhal *et al.* 1989). This radiation was seen to decrease between the *HEAO 3* observations of Fall 1979 and Spring 1980 (Riegler *et al.* 1985). The decrease was most dramatic at energies near 1 MeV, where the continuum level dropped by a factor of 20 or more.

Our observations show no evidence for 0.511 MeV radiation, positronium continuum, or greater-than-0.511 MeV continuum coming from the primary γ -ray source. The spectrum

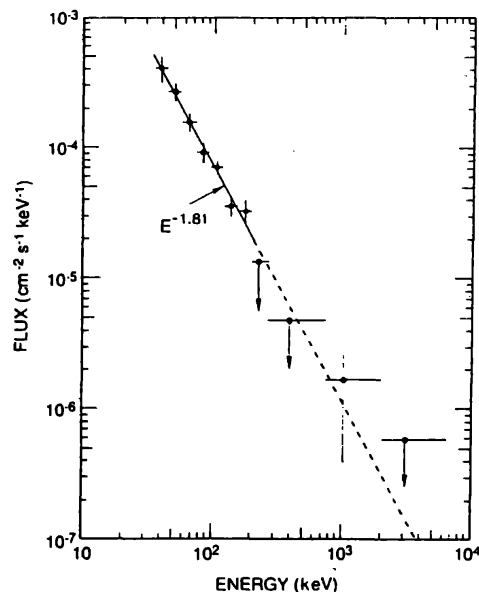


Fig. 2.—Gamma-ray differential energy spectrum for the source of Fig. 1. Upper limits are 2σ .

of Figure 2 is a factor of two or more below the *HEAO 3* Fall 1979 spectrum near 1 MeV. Further, our 0.511 MeV upper limit of $8 \times 10^{-4} \text{ cm}^{-2} \text{ s}^{-1}$ is significantly below the value of $1.85 \pm 0.21 \times 10^{-3} \text{ cm}^{-2} \text{ s}^{-1}$ reported for Fall 1979 (Riegler *et al.* 1981). Our upper limit should also be compared to the 0.511 MeV line flux of $9.8 \pm 1.9 \times 10^{-4} \text{ cm}^{-2} \text{ s}^{-1}$ observed with a non-imaging instrument with 17° FWHM field of view only 18 days after our observation (Leventhal *et al.* 1989). Our 0.511 MeV upper limit does not conflict with this measurement, since our limit applies for a single point in our field of view and is insensitive to the presence of diffuse flux or flux from other sources which could contribute to the non-imaging measurement.

Since we see no evidence of 0.511 MeV or greater-than-0.511 MeV emission from 1E1740.7-2942, we cannot say whether or not this object was the source of positron-annihilation emission seen in other observations. However, 1E1740.7-2942 should be considered as a possible candidate. One possibility is that 1E1740.7-2942 is a stellar-mass black hole system similar to that proposed for Cyg X-1. Indeed, the spectrum of Cyg X-1 in its γ state has similarities to the galactic center spectrum of Fall 1979, showing a hard shoulder of emission above 0.511 MeV with comparable luminosity (Lingenfelter and Ramaty, 1989). Only future imaging observations will definitively establish the location and nature of the source.

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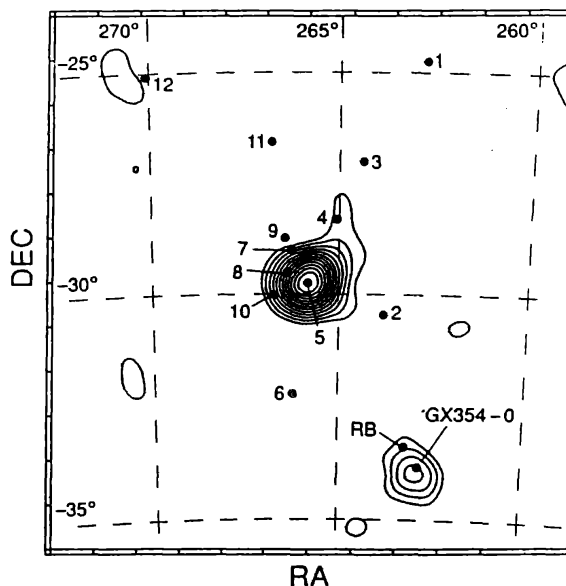


Fig. 3.—Image of the galactic center region from 23 to 122 keV. Contours and known X-ray sources are as in Fig. 1, except for GX354-0 and the "rapid burster", labeled RB (Bradt *et al.* 1979).